

# The radio spectra of galactic nuclei

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**Abstract.** We present a model for the inverted radio spectra of active galactic nuclei as well as the central regions of normal galaxies. The model is based on the unified scenario for active galaxies, stating that the central engines of active galaxies consists of a supermassive black hole surrounded by an accretion disk and a radio jet. The nuclei of normal (i. e. less active) galaxies are supposed to be scaled-down versions of the same phenomenon. We show that the radio emission of a jet component, becoming optically thin to the radio emission of a monoenergetic pair plasma at decreasing frequencies as it moves outward and expands, is well suited to explain the observational results. We present a model calculation for the special case of the nucleus of M 81.

**Key words:** plasmas — radiation mechanisms: Synchrotron — galaxies: active — galaxies: normal — radio emission: galaxies

## 1. Introduction

Radio observations of many active galactic nuclei (AGNs) as well as the nuclei of normal galaxies in the MHz through GHz frequency range reveal inverted radio spectra with spectral indices  $0 \leq \alpha \leq 0.4$  ( $S_\nu \propto \nu^{-\alpha}$ ) (e. g., Kühr et al. 1981, Stickel et al. 1991). In the case of NGC 3031 (M 81), the observed radio spectrum is consistent with optically thin synchrotron emission of a monoenergetic distribution of relativistic electrons, i. e. a spectrum of the shape  $S_\nu \sim \nu^{1/3} e^{-\nu/\nu_c}$ , as was recently suggested by Reuter & Lesch (1996).

Previously, Bartel et al. (1982) proposed a model in which the inverted  $\nu^{1/3}$  spectrum is assumed to be the emission of an inhomogeneous, optically thick source with the magnetic field and electron energy distribution and density varying radially. As was argued in Reuter & Lesch

(1996), this model requires a rather unlikely magnetic field value ( $B \approx 200$  G) and an improbable fine tuning of the radial dependencies to reproduce the  $\nu^{1/3}$  spectrum.

In a more recent paper, Falcke (1996) discussed a model involving optically thin emission of plasma of monoenergetic particles in a continuously filled radio jet. He emphasized the effect of the pressure gradient along the jet leading to an acceleration of the bulk motion, which was claimed to be responsible for the inverted shape of the radio spectrum. For the special case of NGC 3031, Doppler enhancement had to be invoked to account for the observed intensity which, however, appears to be unlikely given the large viewing angle of  $i \approx 60^\circ$  relative to the plane of the entire galaxy.

We favour a similar idea, suggesting that the inverted radio spectra arise from the synchrotron emission of expanding radio jet components. In contrast to the papers by Falcke (1996) and by Reuter & Lesch (1996), we argue that in the case of NGC 3031 it is more likely that the synchrotron emission is not optically thin over the whole range of frequencies. We assume that the jet is not filled continuously with relativistic plasma but that single, separated relativistic blobs move through the jet cone. This is indicated by the correlation of  $\gamma$ -ray flares of blazar type AGNs with the ejection of new radio components from their core regions (e. g., Britzen et al. 1996). Furthermore, we assume that that hydromagnetic turbulences counteract radiative and adiabatic energy losses of the particles in the jet components.

The unified scenario for active galactic nuclei (e. g. Urry & Padovany 1995) states that the central engines of active galaxies consist of a supermassive black hole ( $M \sim 10^6 - 10^9 M_\odot$ ), surrounded by an accretion disk and accelerating a jet of relativistic particles perpendicular to the disk plane. Models based on this idea are well suited to explain, e. g. the broadband radiation and variability of Seyfert galaxies, quasars and BL Lac objects (e. g. Svensson 1997, Dermer, Sturmer & Schlickeiser 1997, Bloom & Marscher 1996). However, jet models for AGNs usually fail to reproduce the radio emission of these objects in the

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cm to mm range since the emitting regions responsible for the optical through  $\gamma$ -ray emission, are optically thick to synchrotron emission in the radio frequency range.

We assume that in a single component of a relativistic jet ejected by a central engine, after the initial phase in which high-energy emission can be produced, a narrow particle distribution with relativistic mean energy  $\langle\gamma\rangle \gg 1$  is built up (Böttcher et al. 1997). As the jet moves outwards, it expands and the system becomes optically thin to synchrotron emission at lower frequencies. We demonstrate that the sum of the synchrotron spectra of a few such components is in agreement with the observed inverted radio spectra and specify this idea to the case of NGC 3031.

## 2. The model

Theoretical investigations on the broadband spectra of AGNs based on relativistic jet models indicate that jets in AGNs most probably contain a relativistic pair plasma where the particles have Lorentz factors above some cut-off  $\gamma_{min}$  (e. g., Sikora 1997, Dermer et al. 1997, Bloom & Marscher 1996). This low-energy cutoff corresponds to the pair-production threshold if the pairs filling the jet components are of secondary origin. The combined action of synchrotron and inverse-Compton losses will then lead to the establishment of a very narrow particle distribution (Böttcher et al. 1997, Achatz et al. 1990) centered at relativistic energies. Such a distribution is called quasi-monoenergetic. After nearly complete dilution of the source photon fields for Compton scattering (synchrotron or external photons) the further evolution of the particles inside such a jet component will be governed by the structure of the global magnetic field as well as synchrotron losses and reacceleration by hydromagnetic turbulences. As long as the jet does not widen significantly, these relativistic plasma components are optically thick to synchrotron emission up to frequencies near the critical frequency  $\nu_c = \frac{3}{2} \nu_e \gamma^2 = 4.2 \cdot 10^6 \text{ Hz } B \gamma^2$ , where  $\nu_e$  is the nonrelativistic gyrofrequency and  $\gamma$  is the electron Lorentz factor. As the plasma component moves further out, the magnetic field is supposed to decrease. At some point, it will become too weak to compensate the dynamical pressure of the relativistic plasma, and the jet starts to widen up. If no particles are created along the jet, this expansion leads to a reduction of the optical depth to synchrotron self absorption which results in the source becoming optically thin at lower frequencies. At the same time the magnetic field decreases, implying a decrease of the critical synchrotron frequency of the relativistic particles.

Our basic idea is that the nuclei of normal galaxies contain scaled-down versions of the same phenomenon as AGNs, i. e. a (not necessarily less massive) black hole, surrounded by a less luminous accretion disk and ejecting a less powerful relativistic jet. The analogy between the core regions of powerful radio galaxies and the radio

cores of normal elliptical and S0 galaxies has been studied in detail by Slee et al. (1994), demonstrating that these objects have similar radio properties.

In order to test the applicability of this model, we consider a simplified case which illustrates the basic concept: We start our calculation at the point where by means of the scenario outlined above a quasi-monoenergetic pair distribution inside a relativistic jet component has been established. Initially, this component, containing electrons and positrons of energy  $\gamma_0 m_e c^2$ , is located at a distance  $z_0$  from the core of the galaxy. It starts to expand freely at the point where the magnetic field becomes too weak to collimate the jet structure. We assume that at this point equipartition holds. The component is supposed to move relativistically along a conical jet ( $z$  direction). The magnetic field declines as  $B(z) = B_0 (z/z_0)^{-1}$  (Blandford & Königl 1979). In the phase of free expansion, the radius  $R$  of the component increases linearly, i. e.  $R(z) = R_0 (z/z_0)$ . We neglect the escape of particles and assume that no particles are created or annihilated. Thus, since we assume that the component expands in all three dimensions, the density  $n$  varies as  $n(z) = n_0 (z/z_0)^{-3}$ . The combined effect of synchrotron losses, adiabatic losses and reacceleration by plasma wave turbulences will, in general, lead to some change in the electron energy. We assume that this cooling (or heating, respectively) is described by  $\langle\gamma\rangle(z) = \gamma_0 (z/z_0)^{-s}$  where  $s$  is considered as a free parameter. From the value of  $s$  which yields the best agreement with the data, one can determine the importance of stochastic acceleration as compared to radiative and adiabatic losses.

The synchrotron spectrum of a narrow relativistic particle distribution centered at  $\langle\gamma\rangle$  does not differ much from the spectrum of a monoenergetic distribution at energy  $\langle\gamma\rangle$  (e. g., Beckert et al. 1997). Therefore we may approximate the emanating synchrotron radiation by the emission of monoenergetic particles. For this purpose, we use the solution given by Crusius & Schlickeiser (1988) for the case that plasma effects (Razin-Tsytovich effect) on the synchrotron emission are negligible. The emissivity is then given by

$$\epsilon_\nu = \frac{n \alpha h}{4\sqrt{3} \gamma^2} \nu C S \left( \frac{\nu}{\nu_c} \right) \approx 2.09 \cdot 10^{-22} \frac{\text{erg}}{\text{s Hz sr cm}^3} B^{2/3} n \gamma^{-2/3} \nu_9^{1/3} e^{-\frac{\nu}{\nu_c}} \quad (1)$$

where  $B$  is in G,  $n$  in  $\text{cm}^{-3}$  and  $\nu_9 = \nu/(1\text{GHz})$ .  $\alpha$  is the hyperfine structure constant,  $h$  is the Planck constant, and

$$C S(x) = W_{0, \frac{4}{3}}(x) W_{0, \frac{1}{3}}(x) - W_{\frac{1}{2}, \frac{5}{6}}(x) W_{-\frac{1}{2}, \frac{5}{6}}(x) \quad (2)$$

where  $W_{\mu, \nu}(x)$  denote the Whittaker functions. The absorption coefficient is

$$\kappa_\nu = \frac{n \alpha h}{4\sqrt{3} m_e \gamma^3 \nu} W_{\frac{1}{2}, \frac{5}{6}} \left( \frac{\nu}{\nu_c} \right) W_{-\frac{1}{2}, \frac{5}{6}} \left( \frac{\nu}{\nu_c} \right)$$

$$\approx 1.53 \cdot 10^{-13} \text{ cm}^{-1} B^{2/3} n \gamma^{-5/3} \nu_9^{-5/3} e^{-\frac{\nu}{\nu_c}} \quad (3)$$

Since the component is assumed to move relativistically relative to the observer, Doppler boosting must be taken into account. Let  $\Gamma$  be the Lorentz factor of the bulk motion,  $\beta_\Gamma = \sqrt{1 - \Gamma^{-2}}$ , and  $\mu$  the angle cosine between the jet axis and the line of sight. Then, the flux received from one plasma component located at a distance  $z$  from the central engine, is

$$S_\nu(z) \approx D^3 \frac{R(z)^2}{d^2} \frac{\epsilon_{\nu_i}(z)}{\kappa_{\nu_i}(z)} \left( 1 - e^{-\tau_{\nu_i}(z)} \right) \quad (4)$$

where  $D = (\Gamma [1 - \beta_\Gamma \mu])^{-1}$  and  $\nu_i = \nu/D$ ,  $d$  is the distance to the source and  $\tau_{\nu_i}(z) \approx \kappa_{\nu_i}(z) R$ .

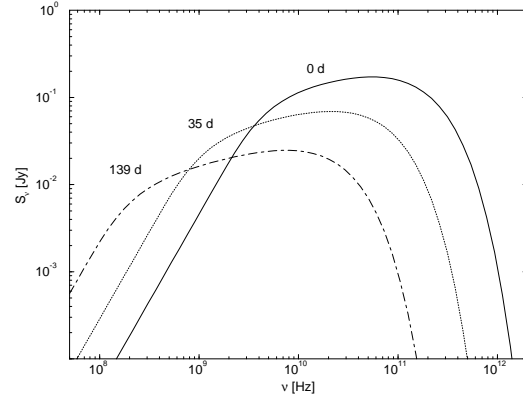
### 2.1. Application to M81

In order to test our idea in the special case of NGC 3031, we use the same data as given in Reuter & Lesch (1996). VLBI measurements revealed a  $\nu^{-0.8}$  dependence of the extent of the source (Bietenholz et al. 1995), being  $\approx 1000$  AU at 8.3 GHz. The radio emission of NGC 3031 exhibits strong variability on timescales of several weeks to months (de Bruyn et al. 1976).

NGC 3031 is seen under an inclination angle of  $i \approx 60^\circ$ . We expect that the orientation of the jet structure does not deviate much from the angular momentum vector of the entire galaxy. Therefore, an inclination angle  $\theta \gtrsim 50^\circ$  and a moderate Doppler factor of  $0.1 \lesssim D \lesssim 1$  seem plausible.

With the parameters found by Reuter & Lesch (1996) for a non-moving source in a steady state in the nucleus of NGC 3031 ( $B \approx 0.4$  G,  $\gamma \approx 400$ ,  $R \approx 1.5 \cdot 10^{16}$  cm,  $n \approx 20 \text{ cm}^{-3}$ ), the source is optically thick up to  $\approx 1$  GHz. We find that with the absence of Doppler enhancement and the restriction on the size from VLBI observations it is difficult to reproduce the radio spectrum of M81 by optically thin synchrotron emission down to frequencies  $\nu \lesssim 1$  GHz. Furthermore, a stationary situation can not explain the frequency-dependent extent of the source.

Nevertheless, given the assumptions quoted above, the inverted spectrum is a natural consequence of the plausible fact that we usually do not observe one single component, but the observed spectrum is the sum of the radio spectra from several expanding plasma blobs. Each blob emits a spectrum of the form  $S_\nu \propto \nu^{1/3} e^{-\nu/\nu_c}$  above the synchrotron self-absorption frequency, and the sum of several such components always has a similar shape. For the model calculation illustrated in Figs. 1 and 2, we used the following parameters:  $\gamma = 250$ ,  $B_0 = 1.2$  G,

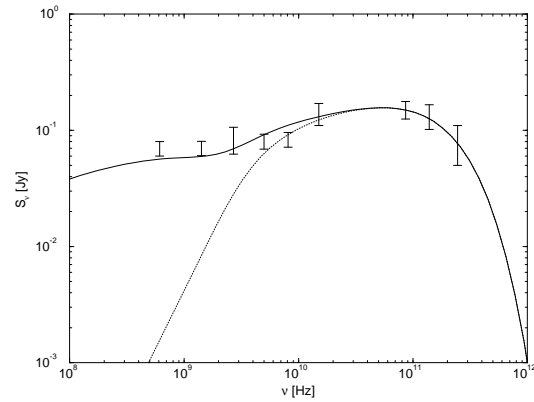


**Fig. 1.** Synchrotron spectra of a single jet component (parameters in the text) at different times (labels). The radius of the expanding jet component is  $R = 8 \cdot 10^{15}$  cm,  $2 \cdot 10^{16}$  cm, and  $5.6 \cdot 10^{16}$  cm, respectively

$R_0 = 8 \cdot 10^{15}$  cm,  $n_0 = 380 \text{ cm}^{-3}$ ,  $s = 0$ , and  $D = 0.4$ . Fig. 1 shows the temporal evolution of the instantaneous synchrotron emission of such a plasma component. The bulk of emission at a certain frequency will be received from the region where the component becomes optically thin to synchrotron emission at this frequency. For  $s = 0$ , this implies the following relation between the extent of the emitting region and the frequency:

$$R \propto \nu^{-\frac{5}{6-5s}} = \nu^{-5/6} \quad (5)$$

which is in excellent agreement with the observed dependence,  $R \propto \nu^{-0.8}$ . The subsequent ejection of new jet components also provides a natural explanation for the observed variability.



**Fig. 2.** The average radio spectrum of M 81. The dotted curve represents the initial synchrotron spectrum ( $t = 0$ )

In Fig. 2, we compare the sum of the instantaneous synchrotron spectra from several radio jet components,

ejected with a period of a few months, to the average radio spectrum of NGC 3031. Given the simplicity of our assumptions, the model spectrum is in good agreement with the observations.

## 2.2. Discussion of other sources

Radio cores of many galaxies show similar properties as observed in M81. Recently, Muxlow et al. (1996) investigated the radio core of the Seyfert 2 galaxy NGC 1068 between 5 GHz and 22 GHz. They could resolve a core component, emitting an inverted spectrum, as well as three more extended components, probably attributable to an expanding jet and with their spectral flux decreasing with increasing frequency. This is well in agreement with an evolution as described above where the core emission represents the  $S_\nu \propto \nu^{1/3}$  portion of an optically thin synchrotron spectrum from monoenergetic electrons, while in the outer parts of the jet (components 1, 3 and 4 in their paper) the decreasing magnetic field has shifted the higher cut-off frequency of the synchrotron spectrum towards  $\sim 20$  GHz.

The statistical investigations of Slee et al. (1994) demonstrate that many E and S0 galaxies with unresolved core regions have inverted radio spectra with spectral indices  $-0.5 \lesssim \alpha \lesssim 0.7$  ( $S_\nu \propto \nu^\alpha$ ) with a mean of  $\langle \alpha \rangle = 0.28$  which indicates the general tendency towards inverted spectra. Since these spectral indices are only determined by no more than three frequencies, the influence of high-frequency cut-offs as well as low-frequency cut-offs due to synchrotron self-absorption or free-free absorption in individual sources can not be fixed from these measurements. The generally inverted radio spectra of low and medium power with spectral indices near the value of  $1/3$  may therefore be regarded as a hint towards synchrotron emission from quasi-monoenergetic electrons.

It should be noted that in the case of our galactic center, Sgr A\*, the assumption of a quasi-stationary situation as discussed by Duschl & Lesch (1994) and by Beckert et al. (1997) is more plausible. In this source, the power-law spectrum of index  $\alpha \approx 1/3$  (Zylka et al. 1995) is restricted by a stationary low-energy cut-off near 1 GHz, and VLBI measurements resolved the central source down to scales of  $\sim 10^{13}$  cm without indicating the presence of a jet. Furthermore, the extent of the source is consistent with being independent of frequency. All these findings render it unlikely that, also in this case, we observe the synchrotron emission of a jet. The reason for this is probably that there is not sufficient material in the inner parsec of the galaxy, usually denoted as the central cavity, to fuel the central black hole, thus preventing the formation of a powerful accretion disk and a jet.

## 3. Summary

Based on recent calculations about the fate of relativistic electron distributions in the vicinity of strong sources of radiation we can explain the physical origin of inverted radio spectra in galactic nuclei. High energy emission processes (inverse Compton scattering of UV-photons to  $\gamma$ -ray energies) produce a quasi-monoenergetic distribution function. Such quasi-monoenergetic electrons are injected into a plasma jet in the form of distinct components rather than in a continuous relativistic outflow, as indicated by recent observations. The time evolution of these components including the evolution of the optical depth of the radio emission of quasi-monoenergetic electrons along the propagating jet accounts for the observed inverted radio spectra.

Our model bridges the gap between the high energy behaviour of galactic nuclei and the radio emission. If the  $\gamma$ -flux of galactic nuclei is of purely leptonic origin via inverse Compton scattering on UV-photons, the observed inverted radio spectra are a natural consequence of the spatial and time evolution of the relativistic electron distributions involved in both  $\gamma$ -ray and synchrotron radiation.

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